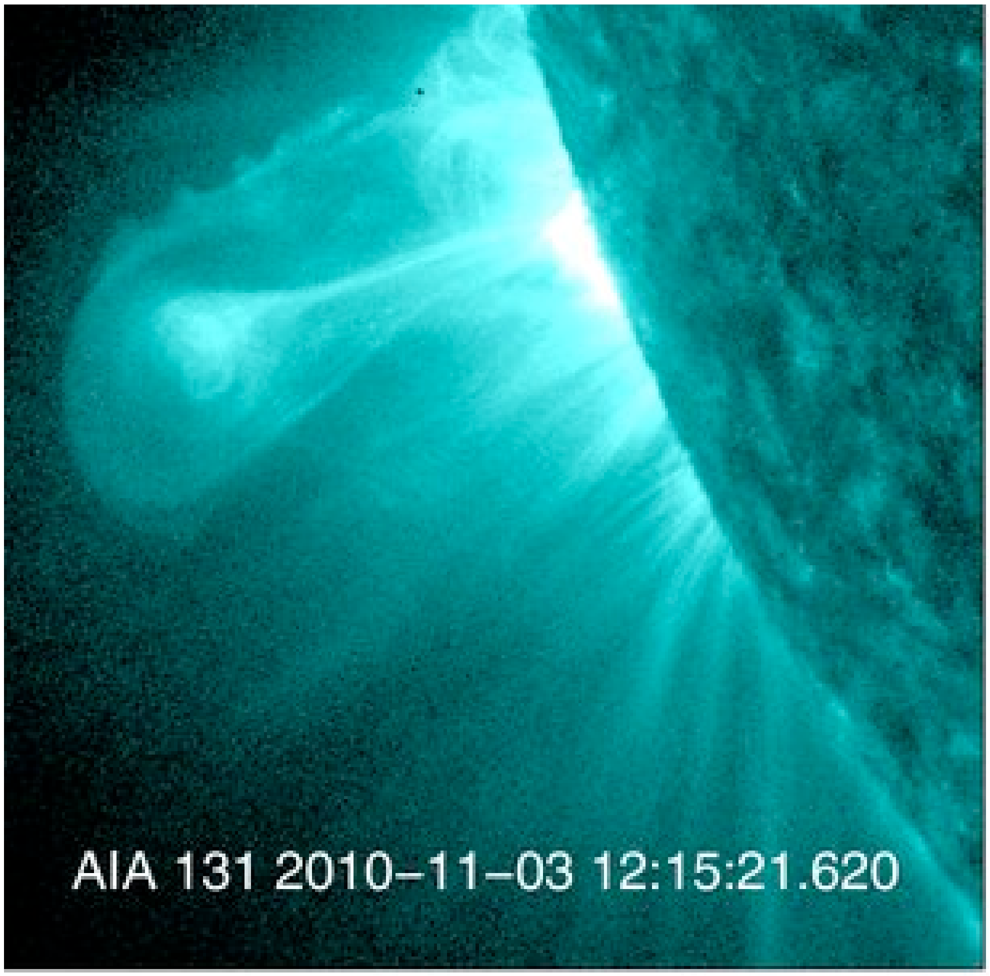
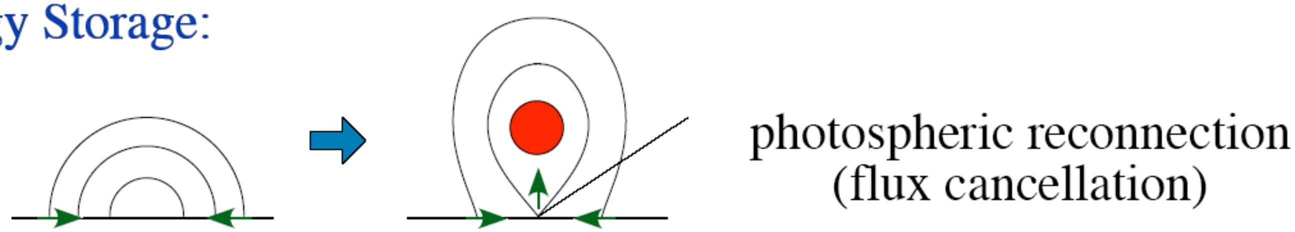
Magnetic Reconnection in Solar Flares

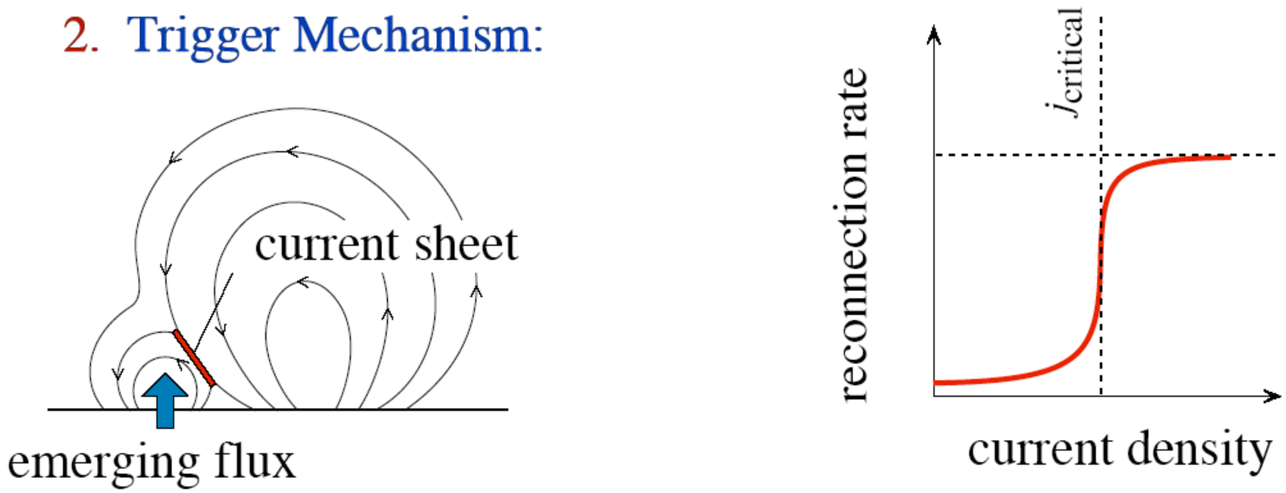


Possible Roles for Reconnection:

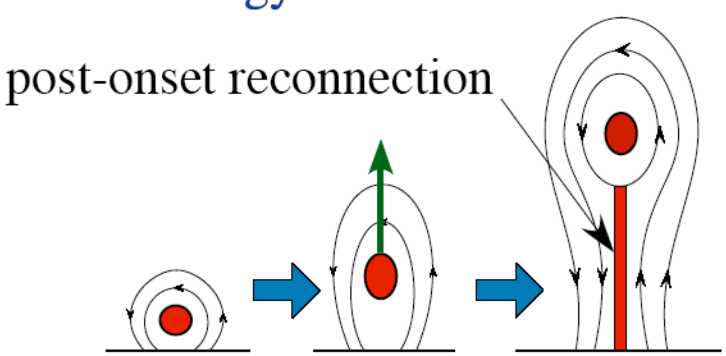
1. Energy Storage:



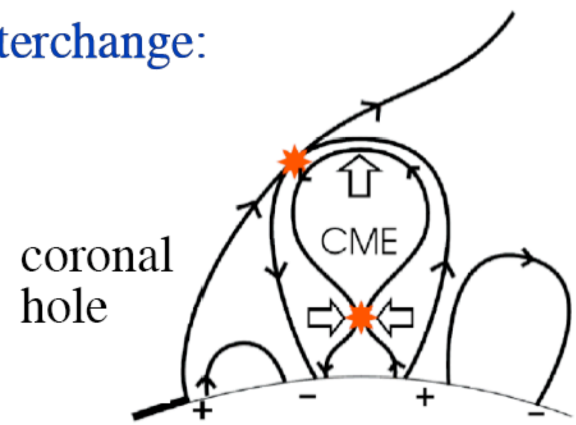
2. Trigger Mechanism:



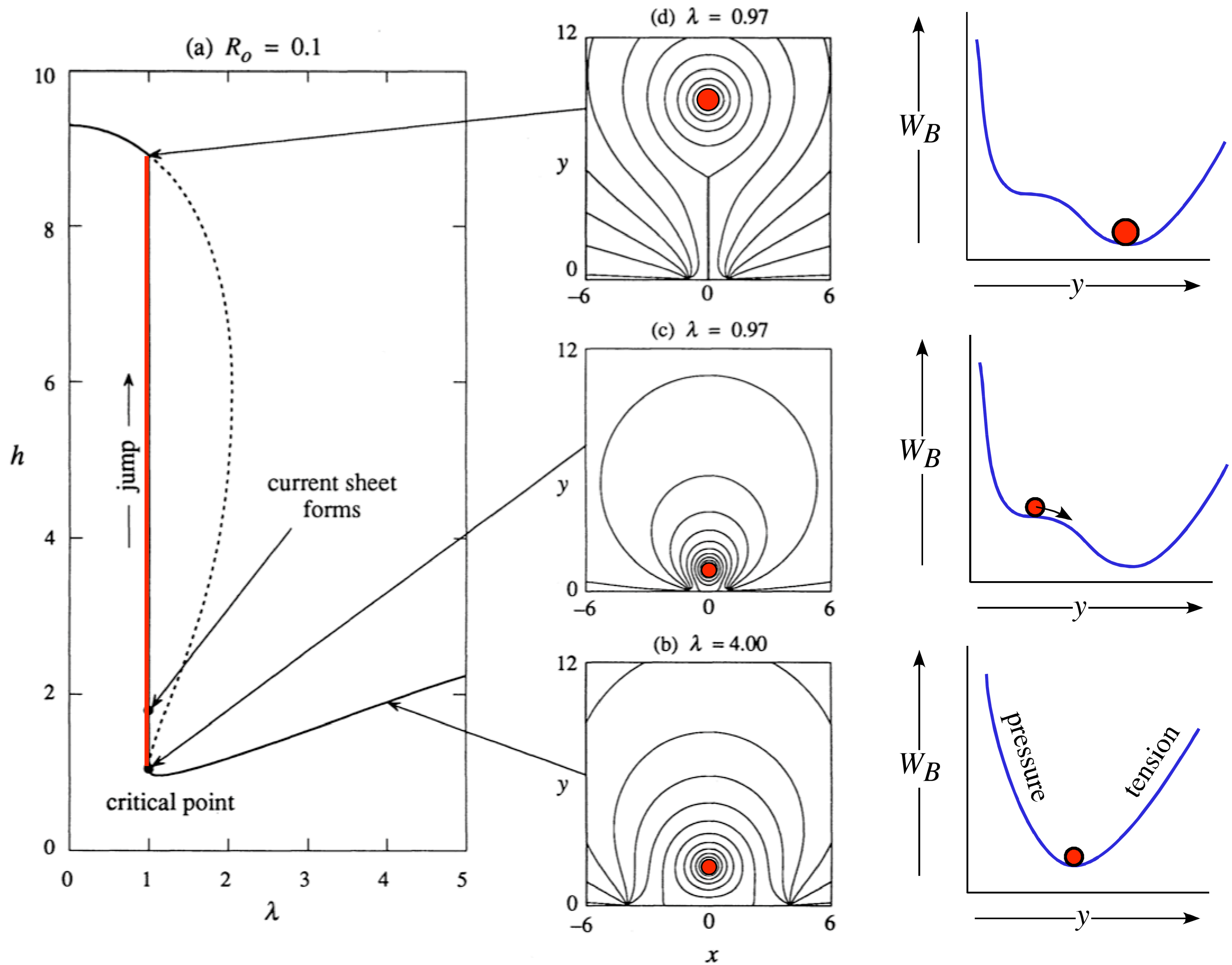
3. Energy Release:



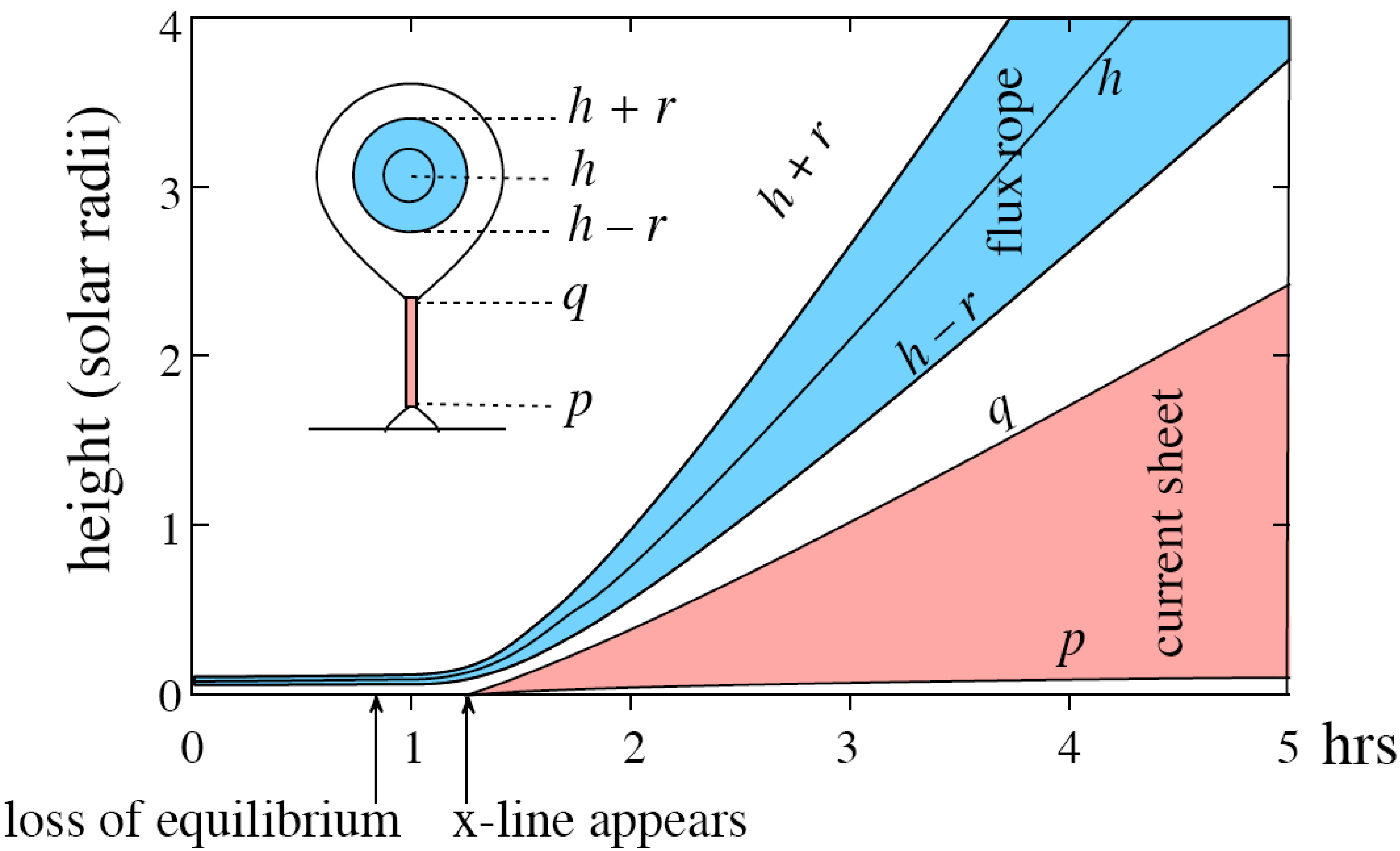
4. Interchange:



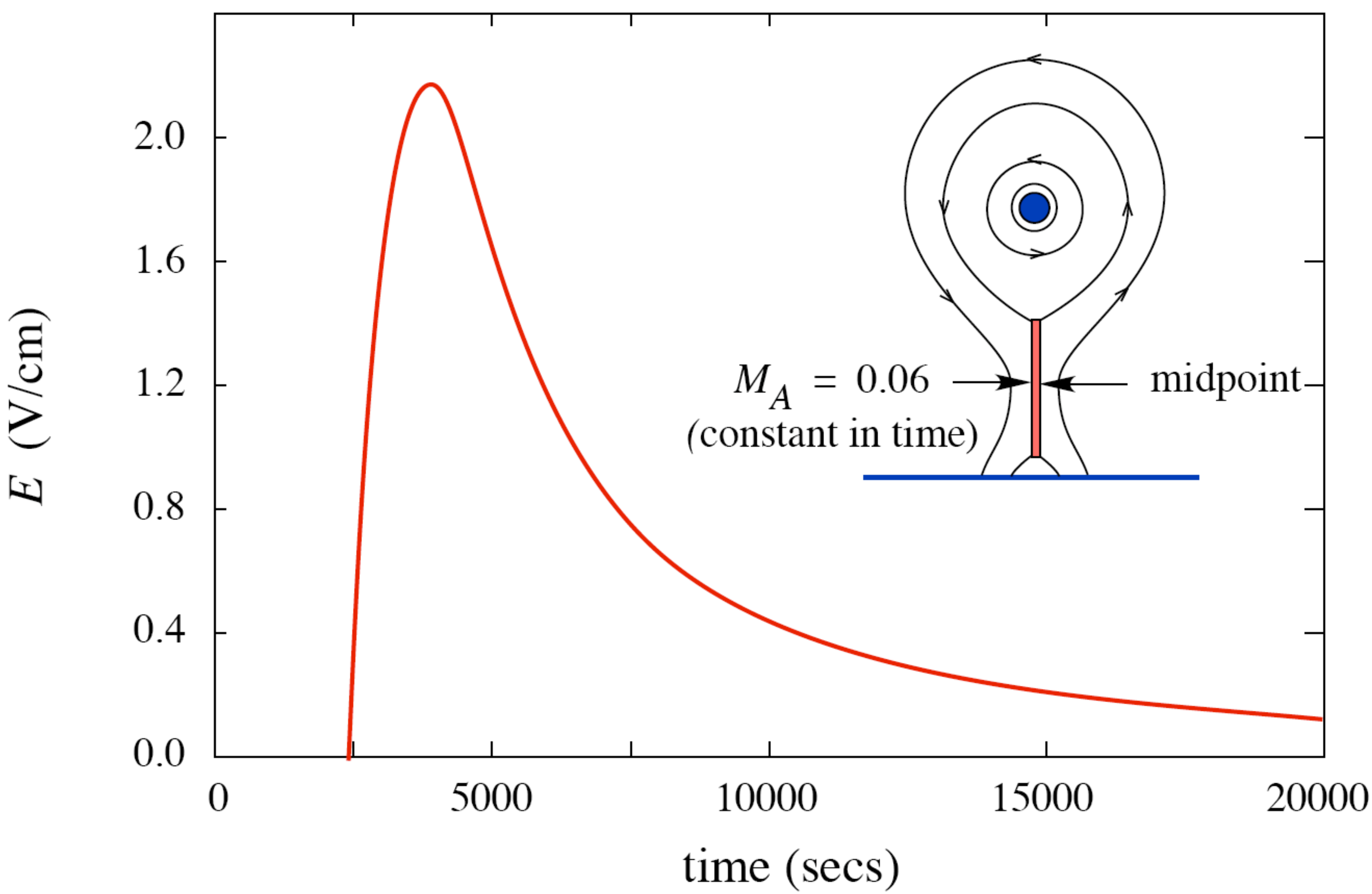
Loss of Equilibrium Model



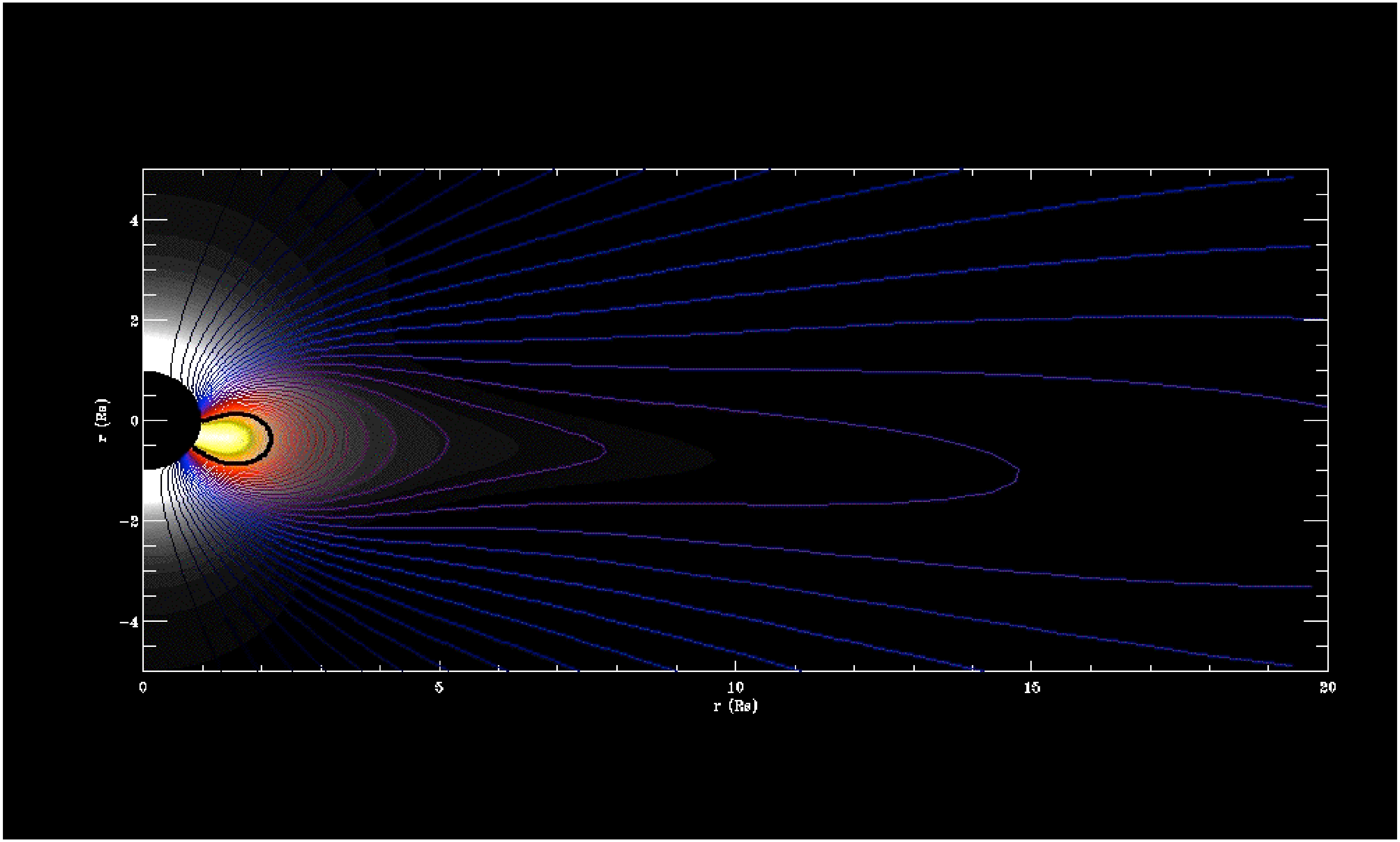
Trajectories



Reconnection Electric Field for Constant Alfvén Mach Number

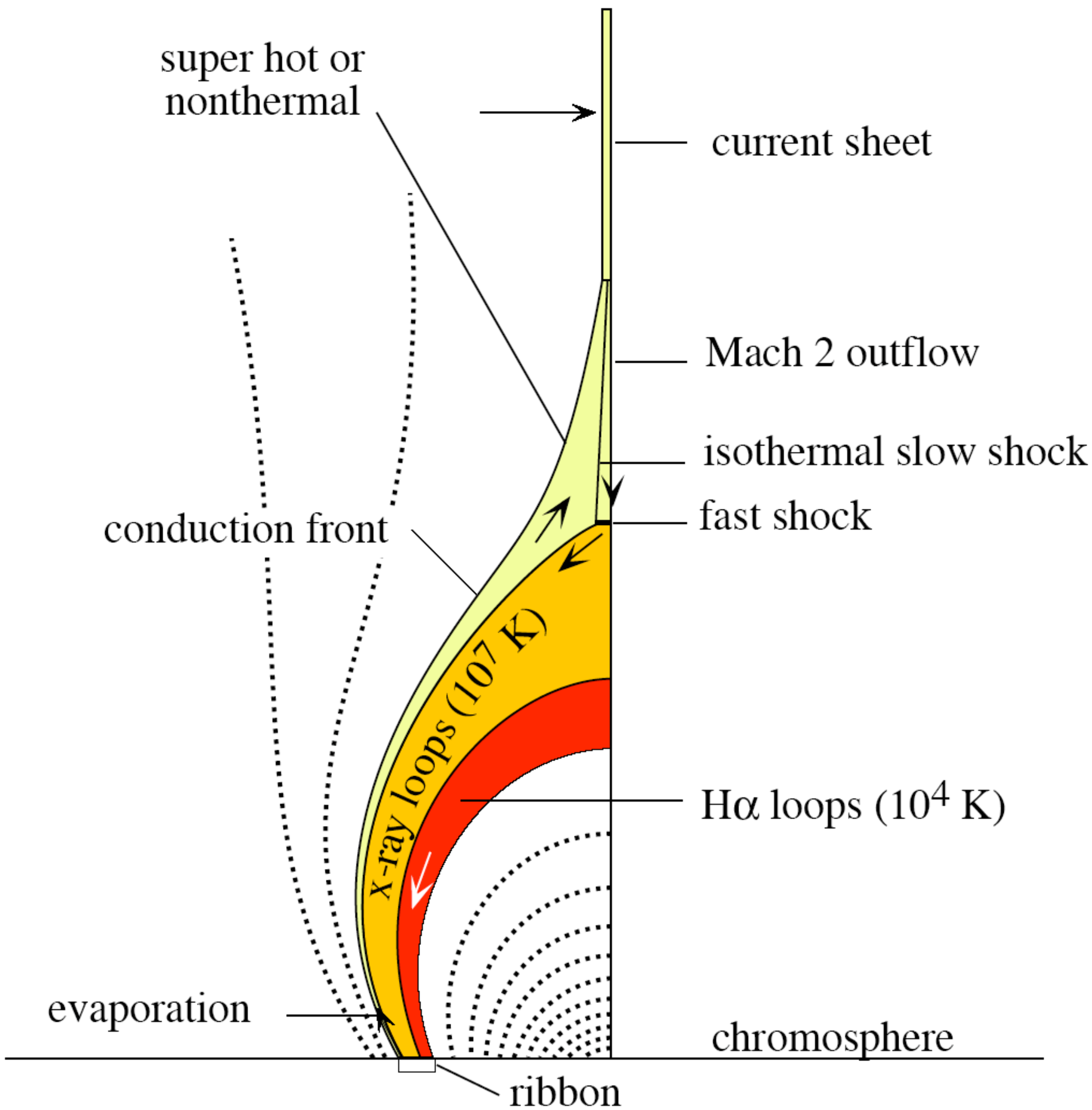


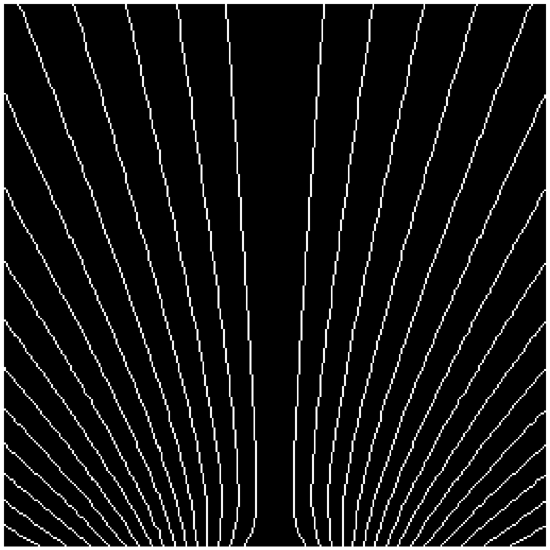
Predictive Science CME Simulation



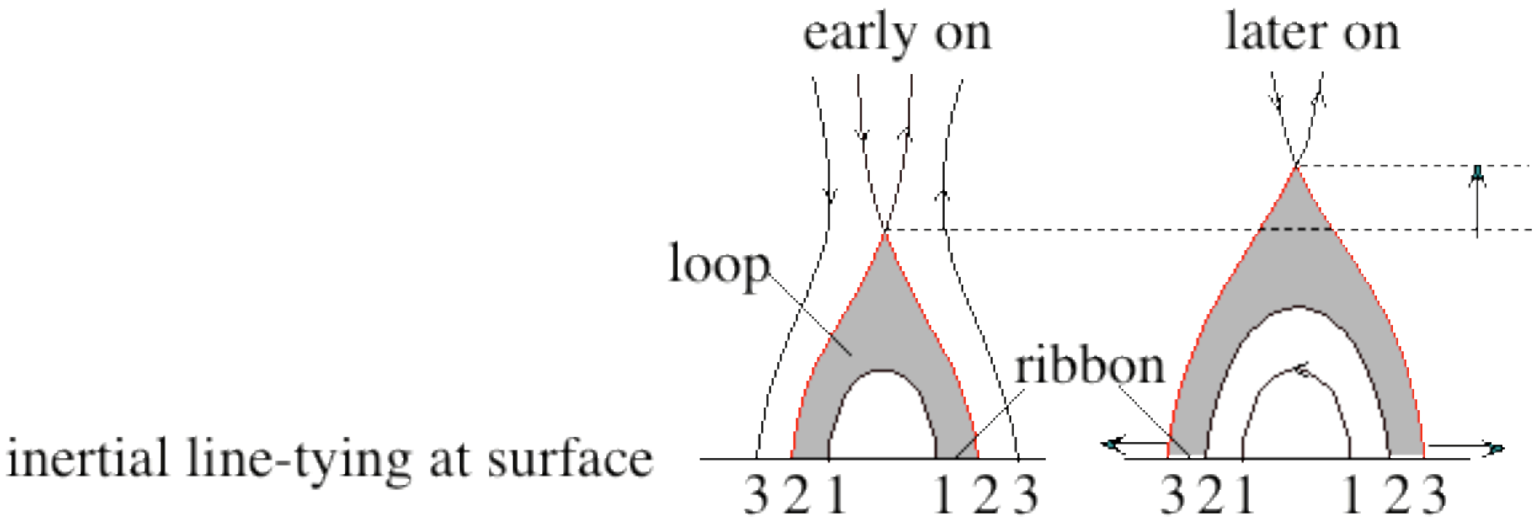
Linker et al. (2001)

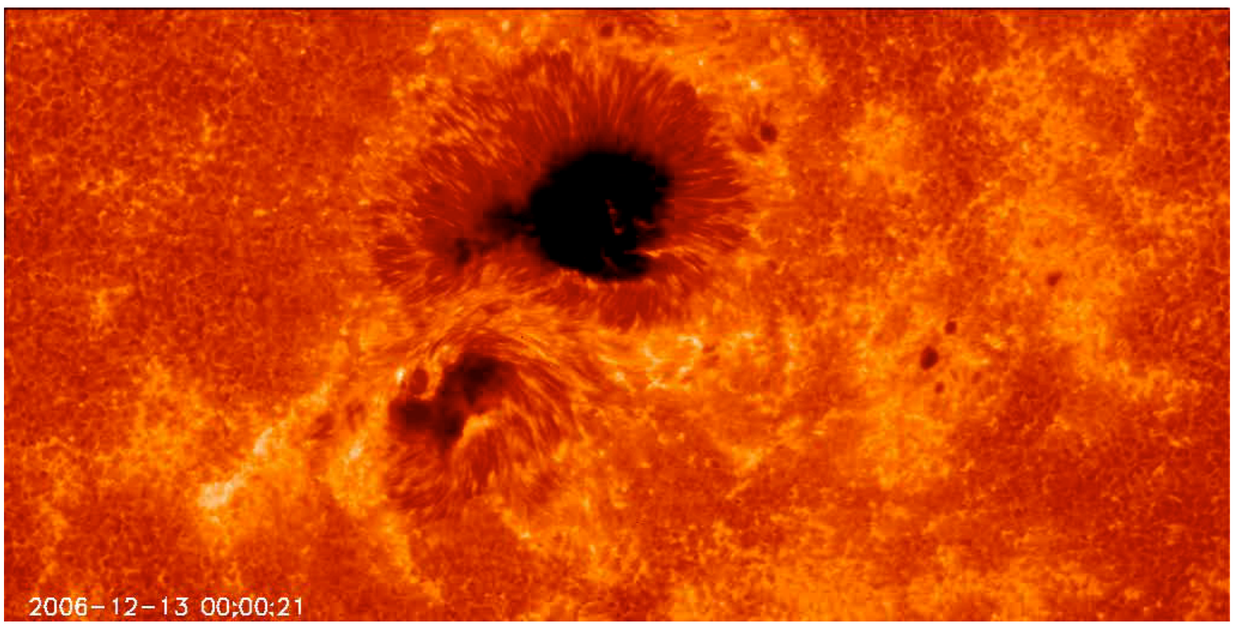
Flare Loop System



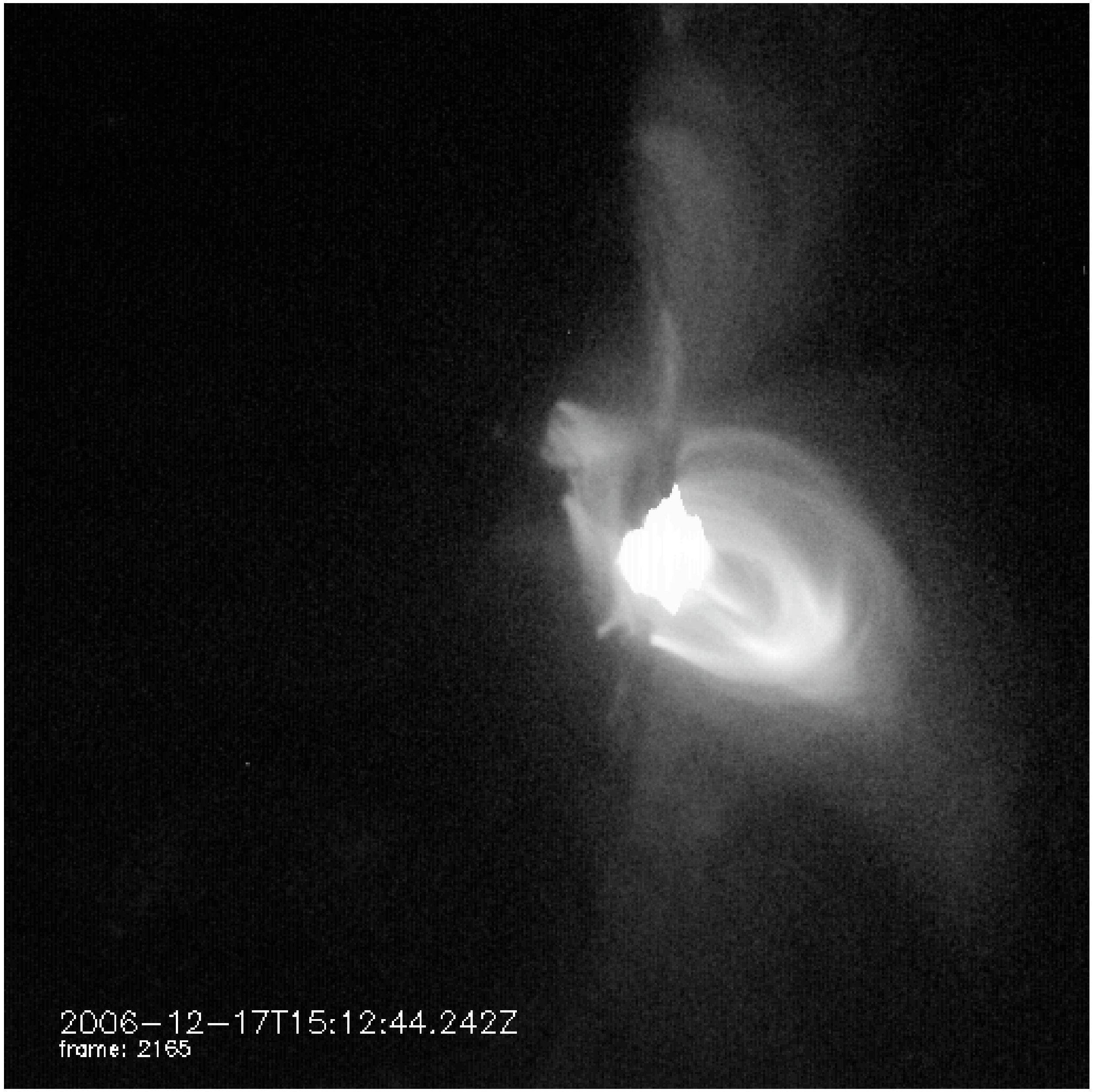


Apparent Motion of Loops & Ribbons



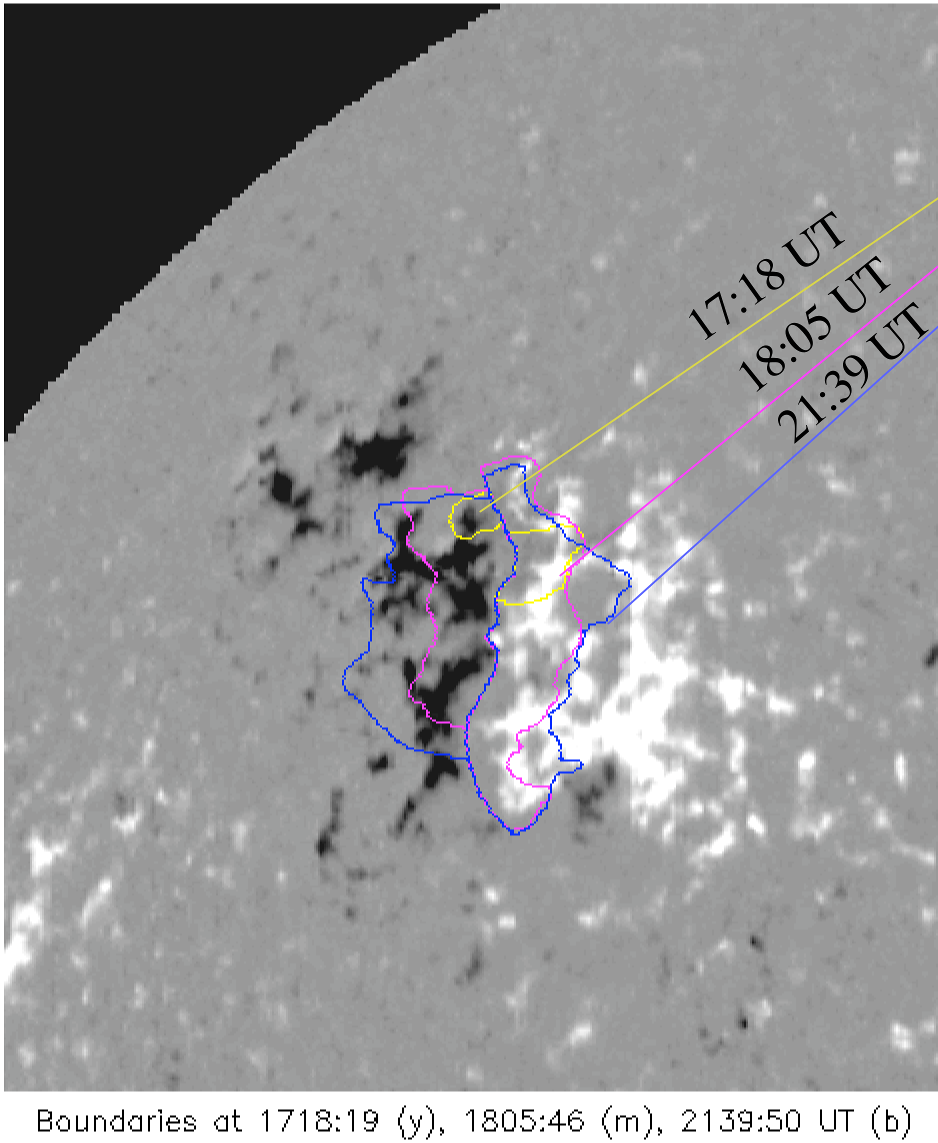


Shinkrage of Flare Loops Observed by Hinode XRT



Flare Reconnection Rate from Observations

NSO/Kitt Peak Magnetogram 18 Dec 1998



area σ swept out by flare ribbons

newly re-closed flux:

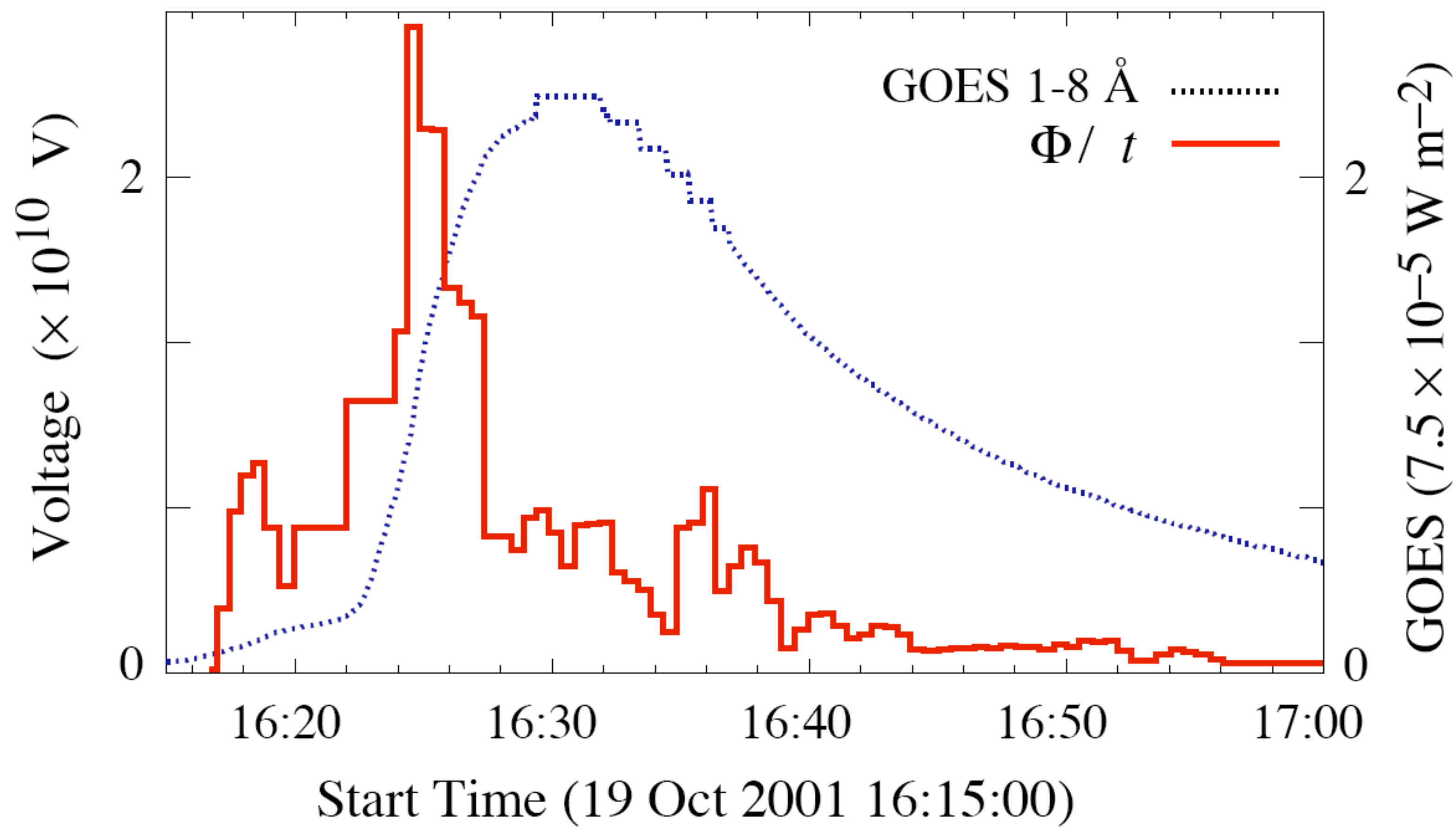
$$\Phi = \iint \mathbf{B} \cdot \mathbf{d}\sigma$$

voltage drop along *x*-line:

$$\boxed{\int \mathbf{E} \cdot \mathbf{dl} = \frac{d\Phi}{dt}}$$

Flare Reconnection Rate

Observed Reconnection Rate for X1.6 Flare



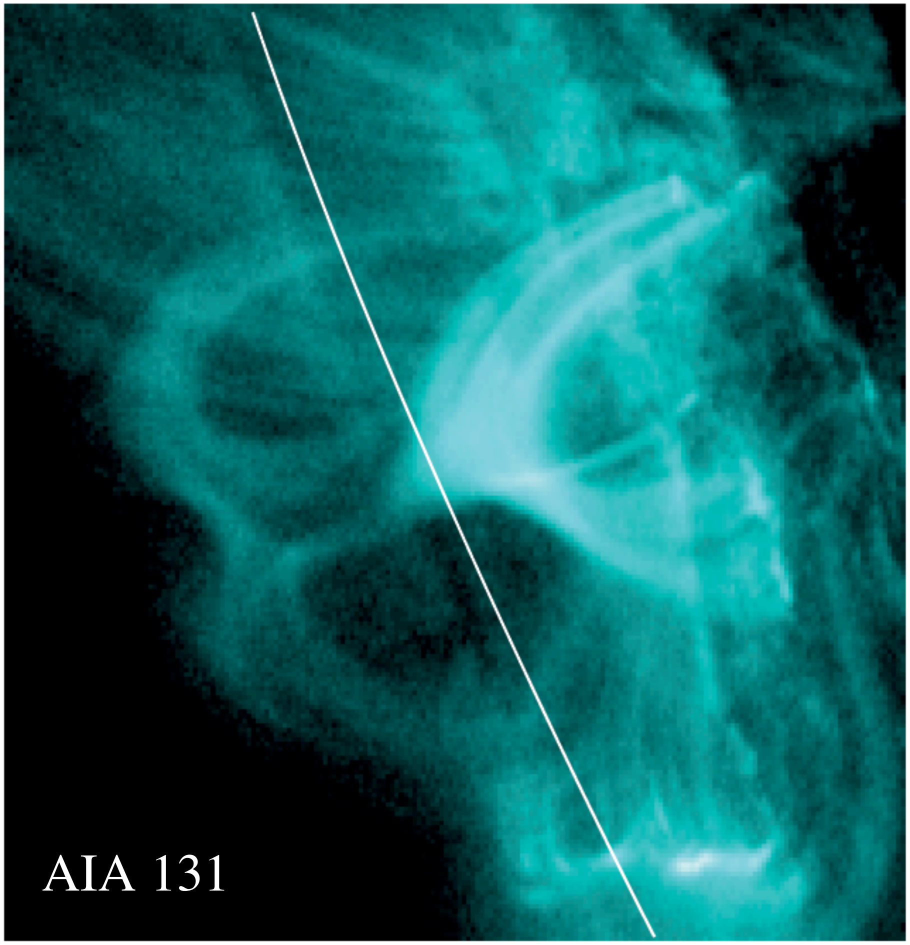
$\boxed{E_{\mathrm{reconnect}} \sim 2 \text{ volts/cm}}$

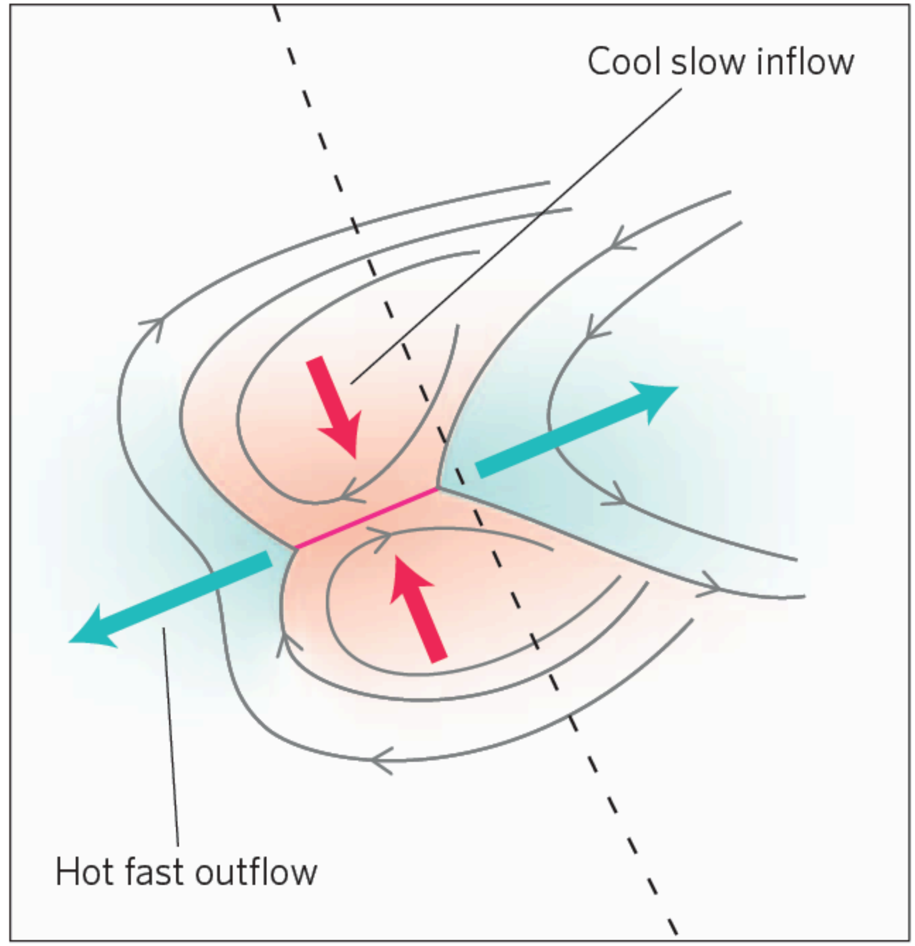
$\boxed{E_{\mathrm{Dreicer}} \sim 10^{-6} \text{ volts/cm}}$

after Qiu et al 2004

Observations of Reconnection Flows

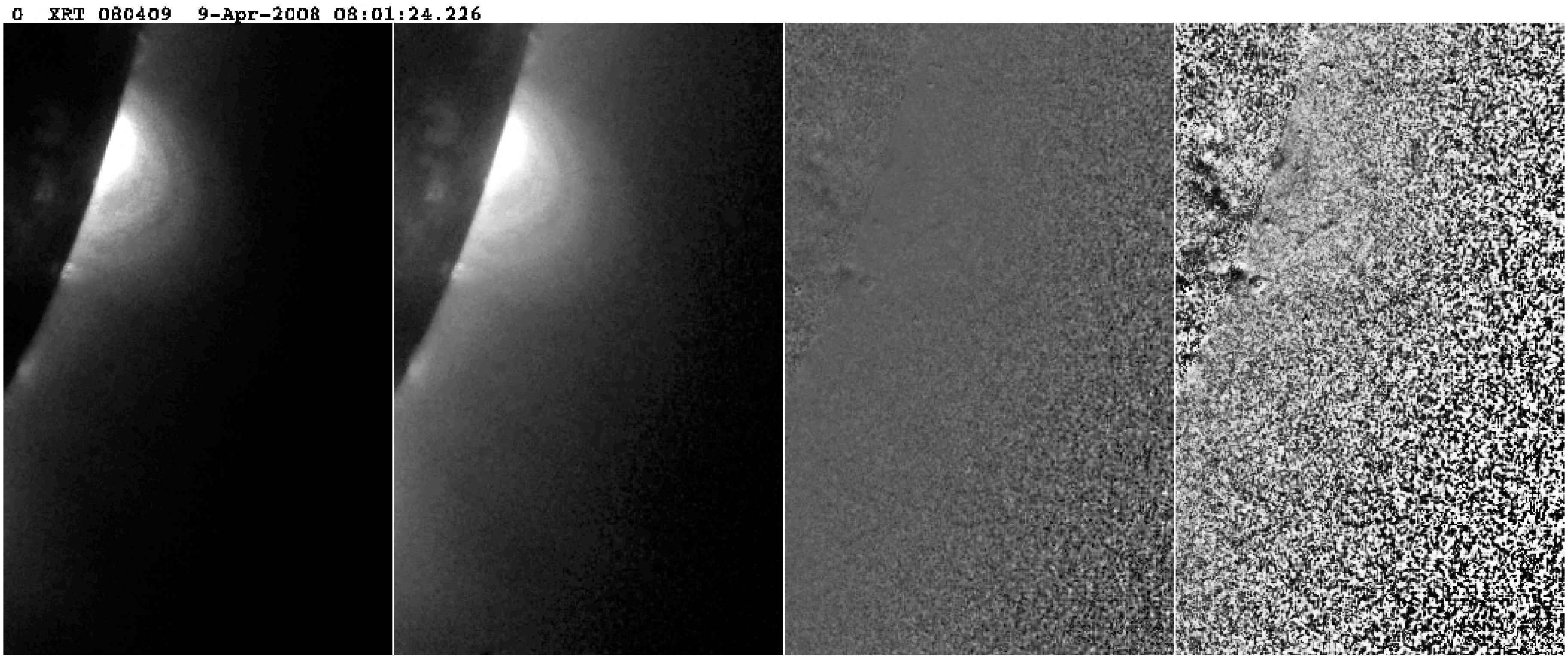
Non-eruptive event of 17 Aug 2011



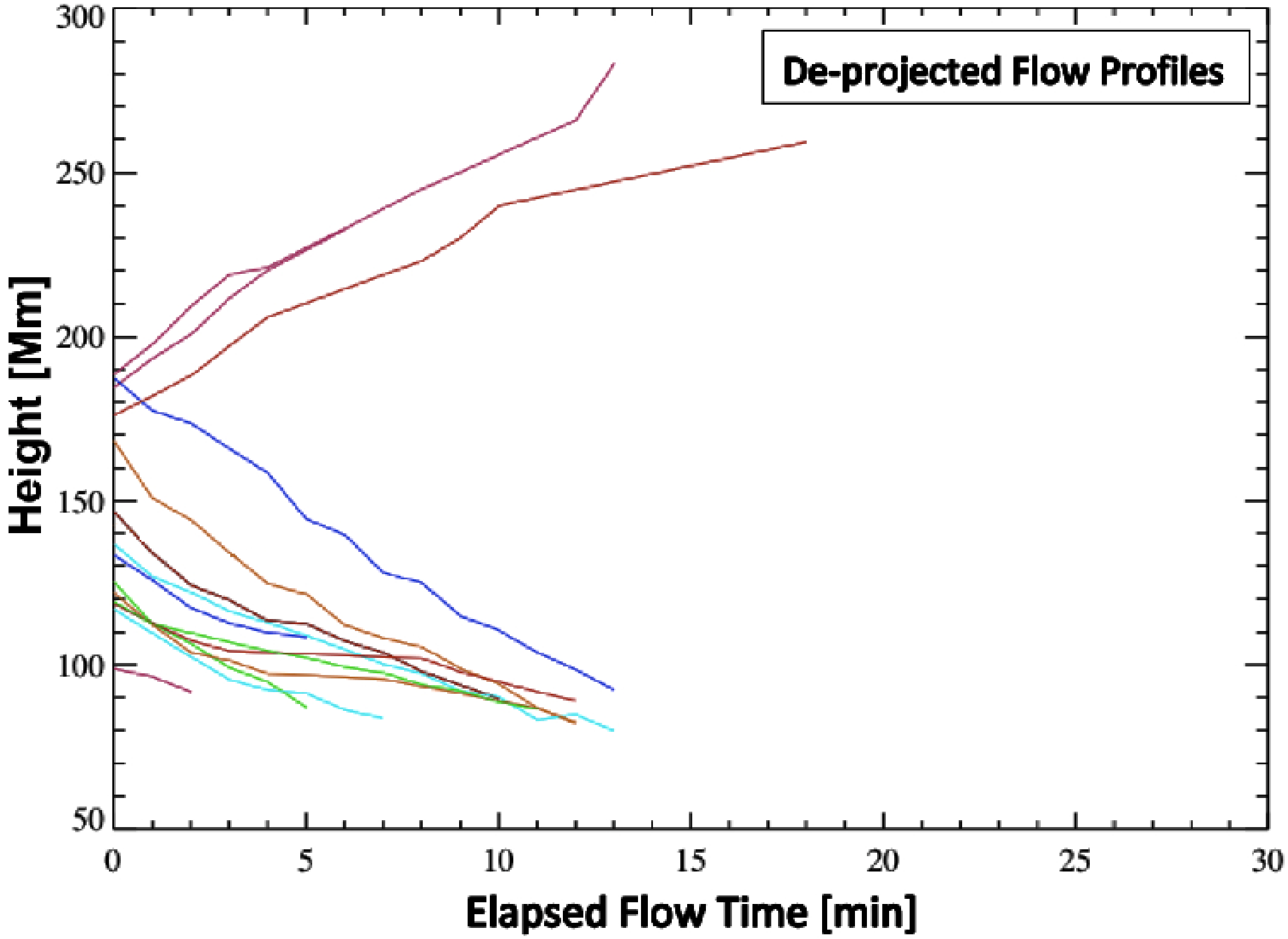


Su et al. 2013

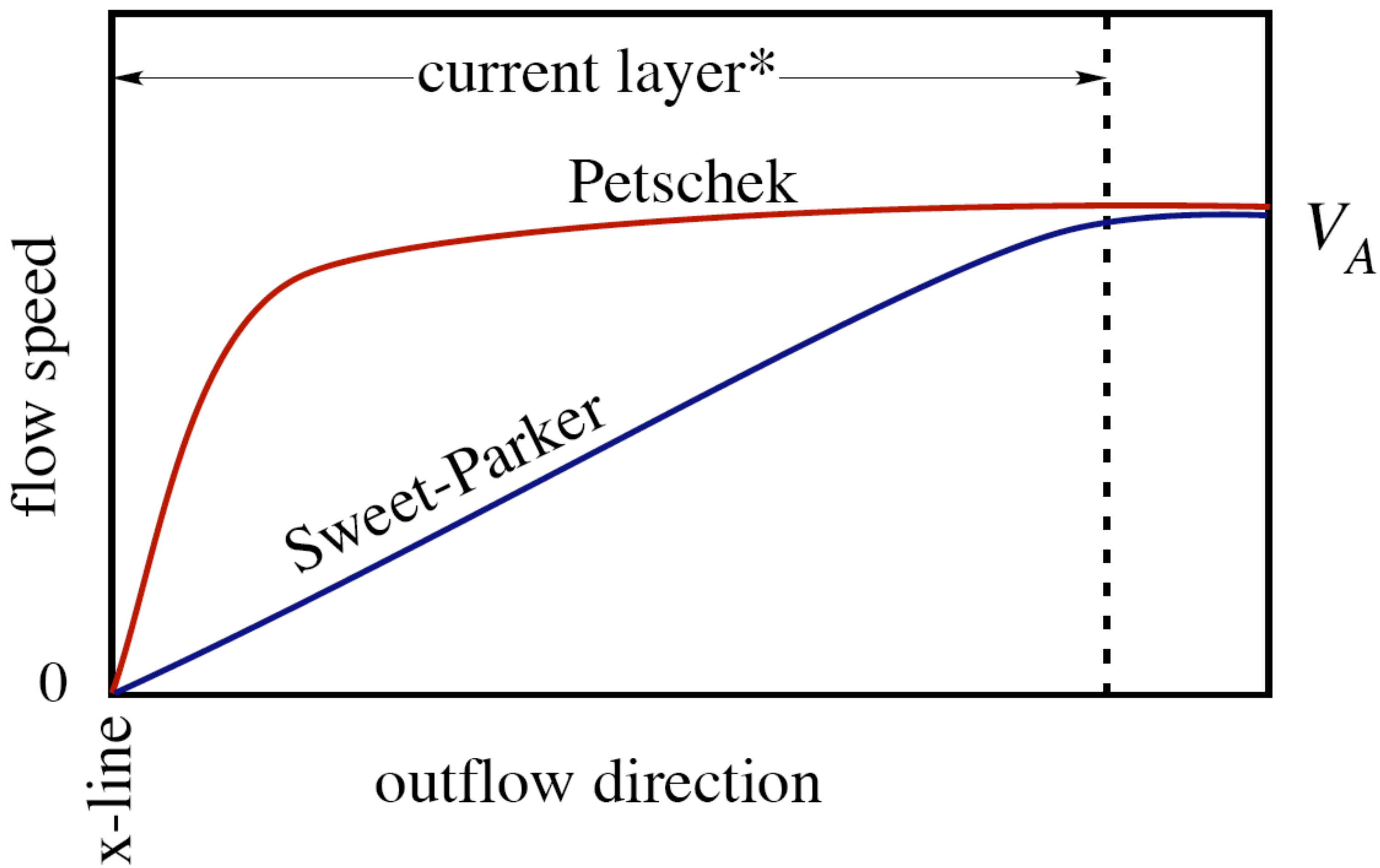
Tracking of Small Features in Current Sheet



Savage et al. 2010


De-projected Flow Profiles
Height [Mm]
Elapsed Flow Time [min]
300
250
200
150
100
50
0
5
10
15
20
25
30

Outflow Profiles for Petschek and Sweet-Parker Reconnection

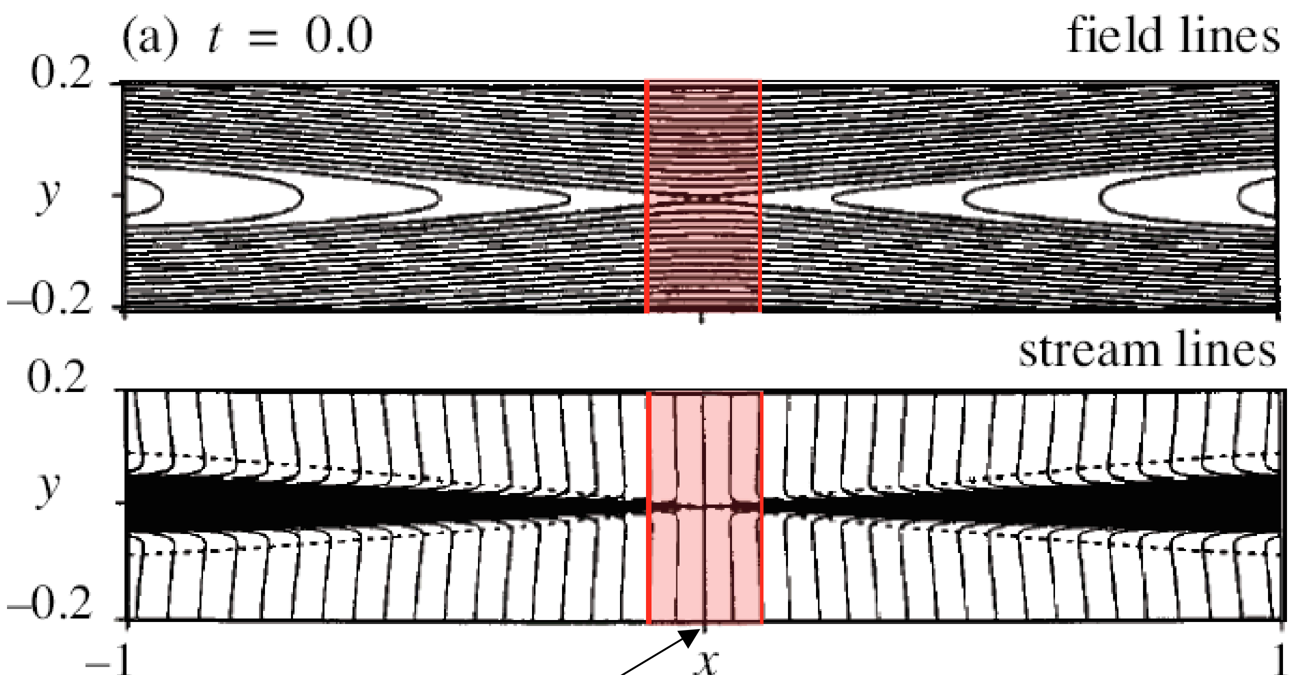


*diffusion region + slow shocks

Early MHD Numerical Simulations

Yan et al. (1992)

Fast-Petschek solutions not observed when the resistivity is uniform.



region of enhanced resistivity

Incompressible Time-Dependent Nozzle Equations for Resistive MHD

$$a_t = -(Va)_x - Vb/B + \eta/a$$

$$b_t = -(Vb)_x + \boxed{(\eta B/a)_x}$$

$$(Va)_t = (V^2 a)_x - aBB_x + Bb$$

$$(\,)_t = \frac{\partial}{\partial t} \qquad (\,)_x = \frac{\partial}{\partial x}$$

a: thickness of current layer

V: outflow

b: perpendicular interior field

B: parallel exterior field

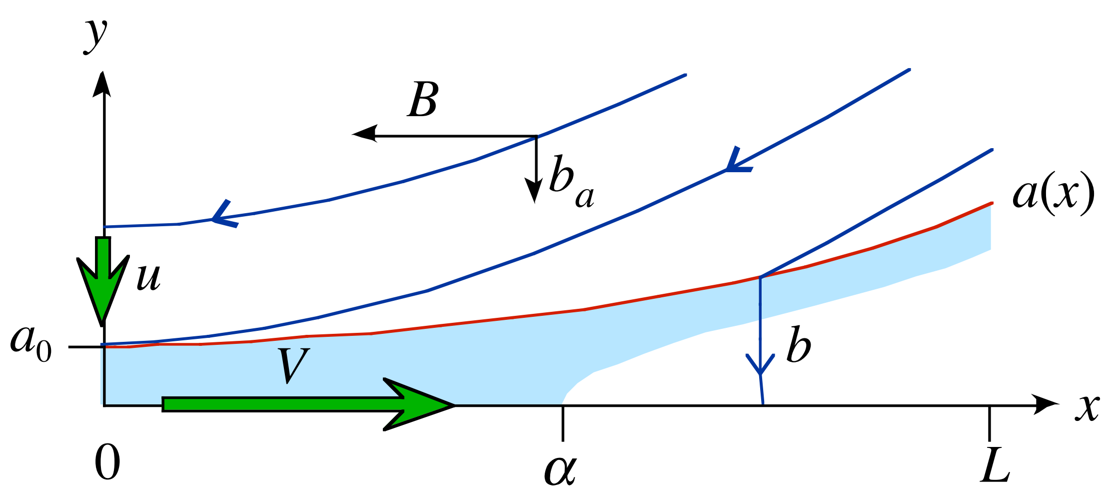
η: magnetic diffusivity

u: inflow

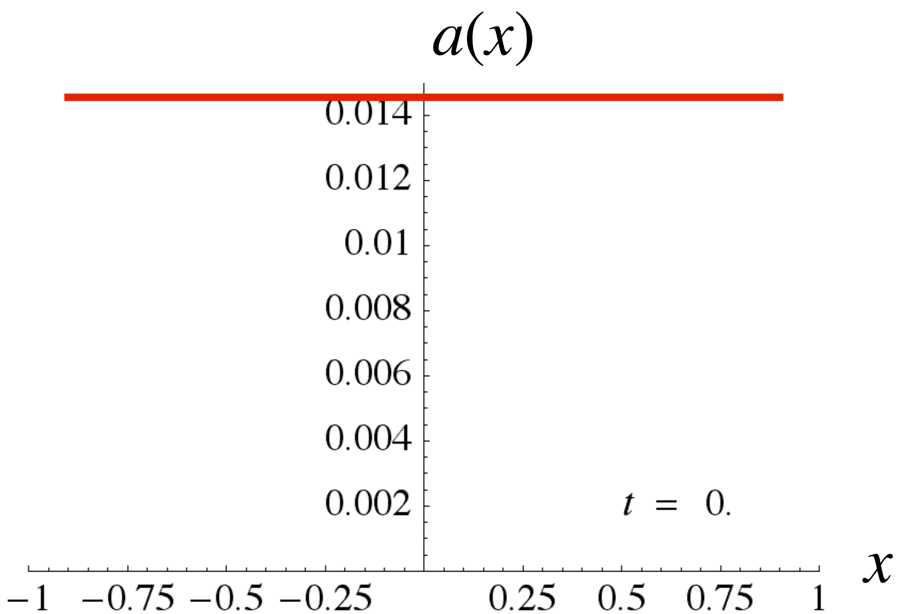
b_a: perpendicular exterior field

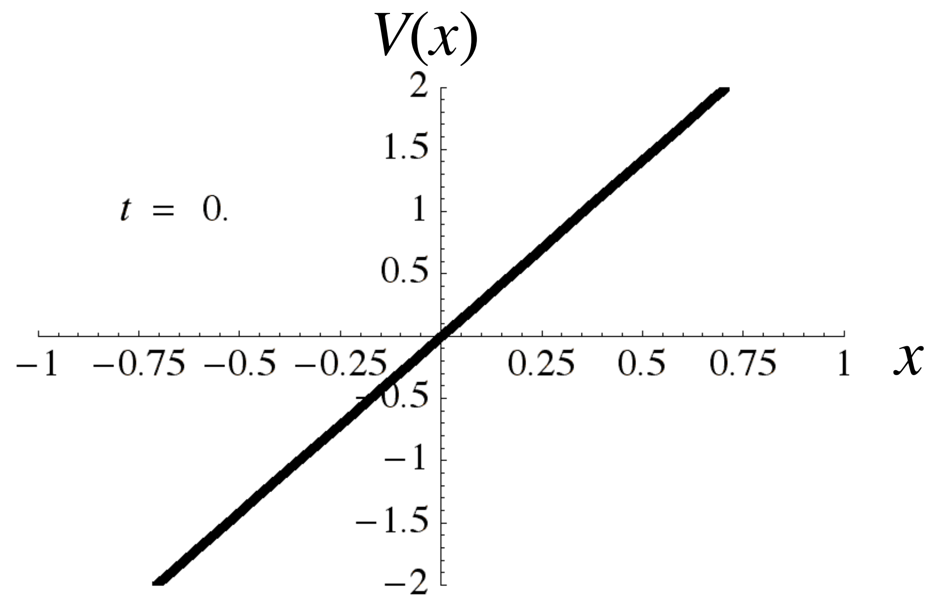
α: diffusion region length

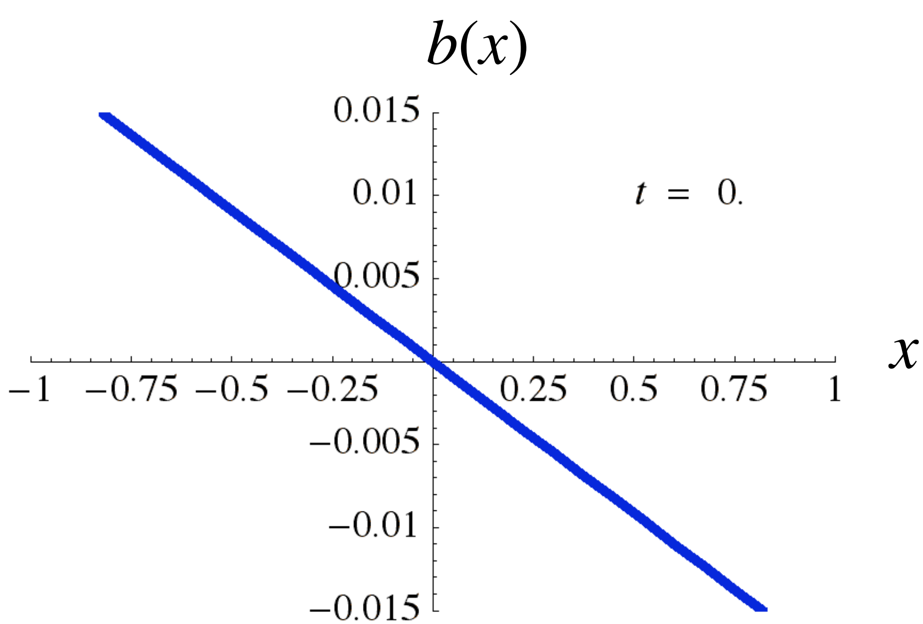
L: global scale length



Evolution of Non-Uniform Resistivity Solutions







$\eta(x) = \eta_0 \,\mathrm{Exp}[-(x/l)^2]$

$\eta_0 = 1/\mathrm{Lu} = 0.0001$

$l = 0.25$

$\boxed{\text{final } M_A = 0.0353}$

How to Calculate Reconnection Rate

Reduction to steady-state:

$$(xV)_x \;=\; V^{-1} - \eta(x)\, M_A^2\, x^{-1}\;.$$

(equation of Vasyliunas 1975)

Most solutions of this equation have an unphysical singularity!

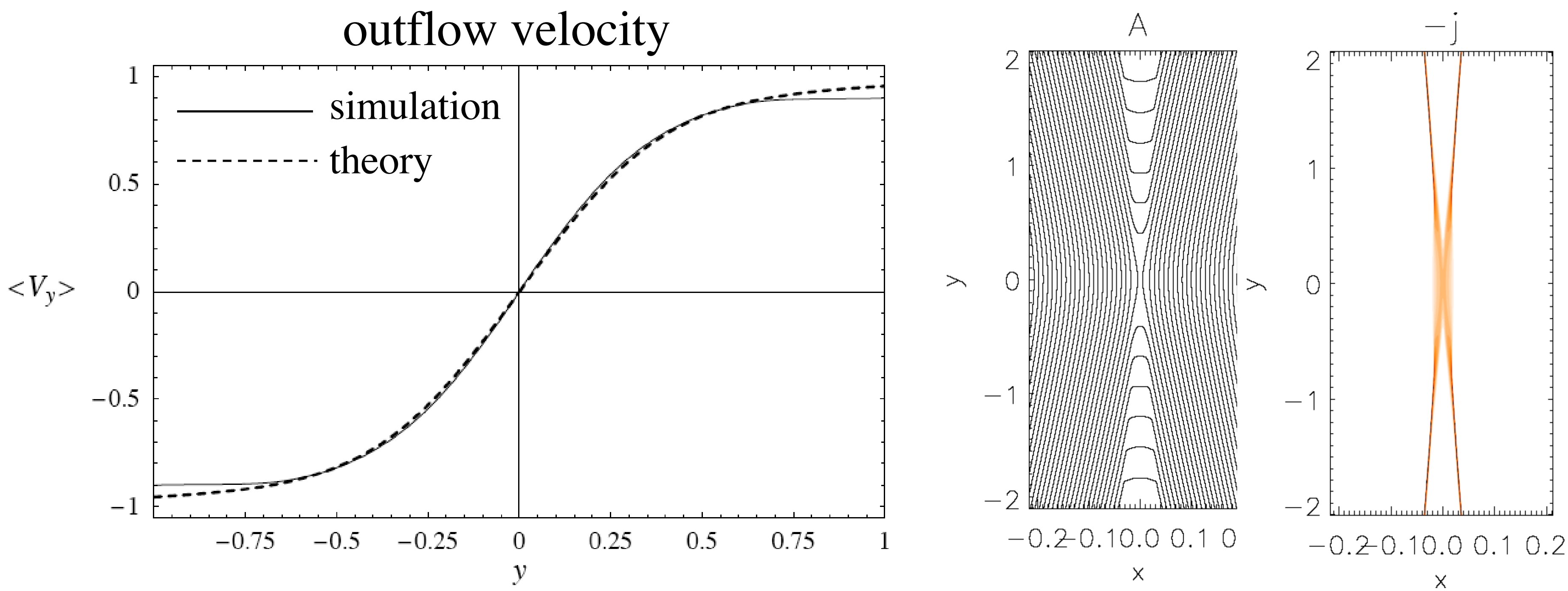
Taylor expand steady-state equation:

$$V(x) \;=\; V_1 x + V_3 x^3 + \cdots$$

Eliminate singular solutions by requiring convergence:

$$\boxed{\lim_{n\to\infty} \left| V_n(M_{A\ \text{stable}}) \right| \;=\; 0\;.}$$

2D MHD Simulations for $\eta(x) = \eta_0 \, \mathrm{Exp}[-(x/l)^2]$

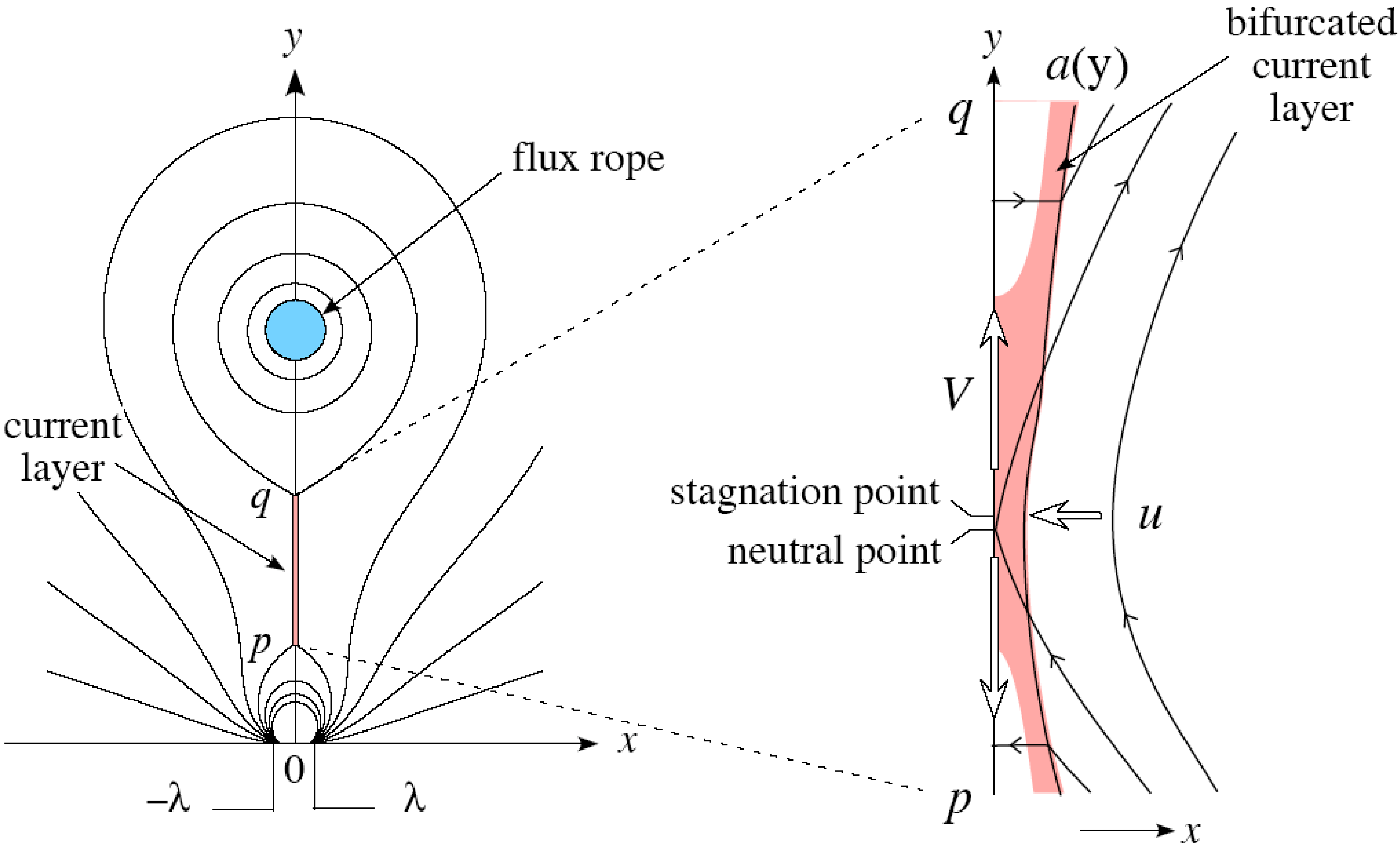


rate predicted by analytical theory: $M_{Ai} = 0.0370$
rate occurring in numerical simulation: $M_{Ai} = 0.0353$
4.9% difference

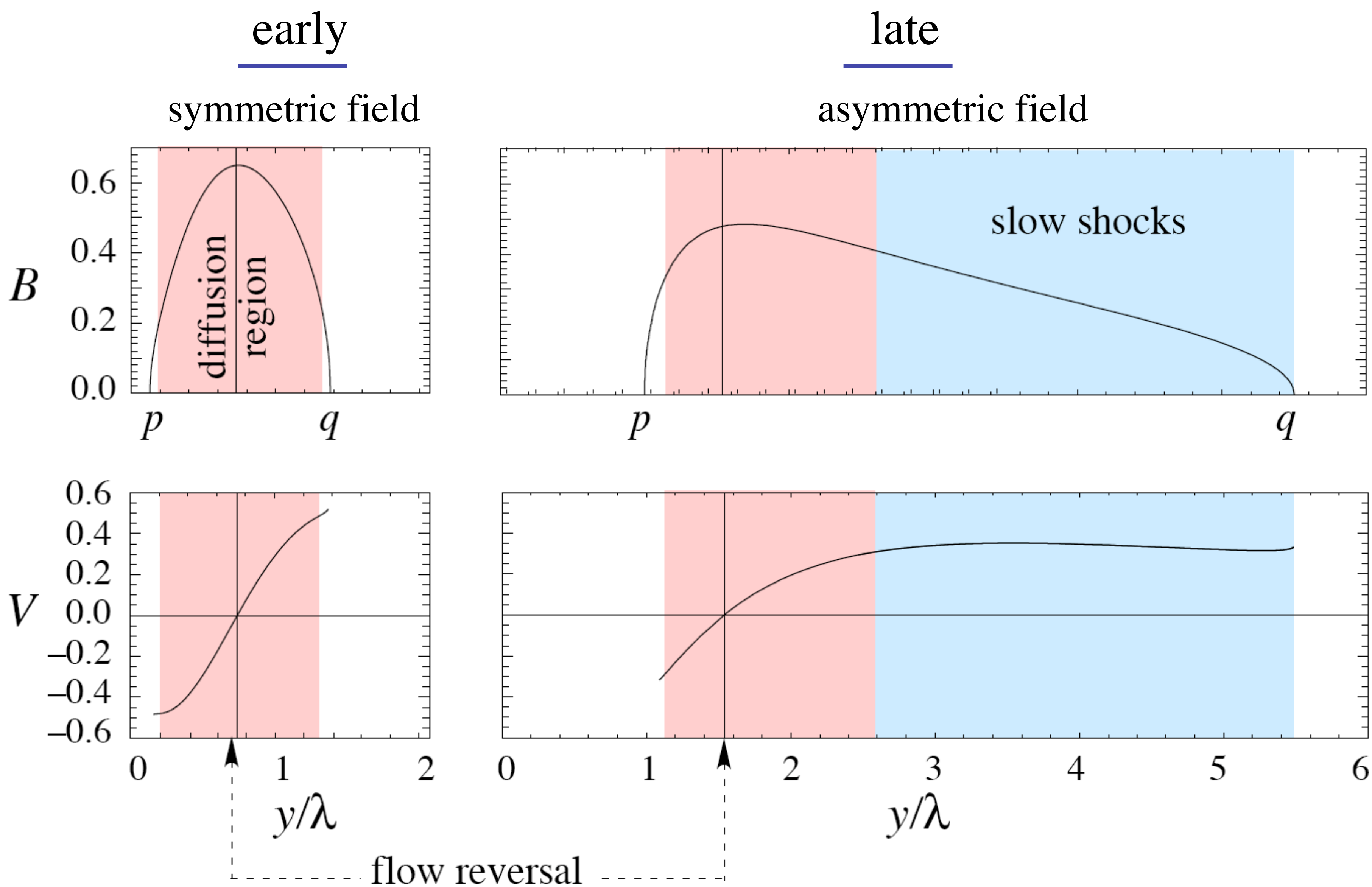
There are no free parameters in the theory.

Baty et al. (2014)

Application to Simple Flare Model

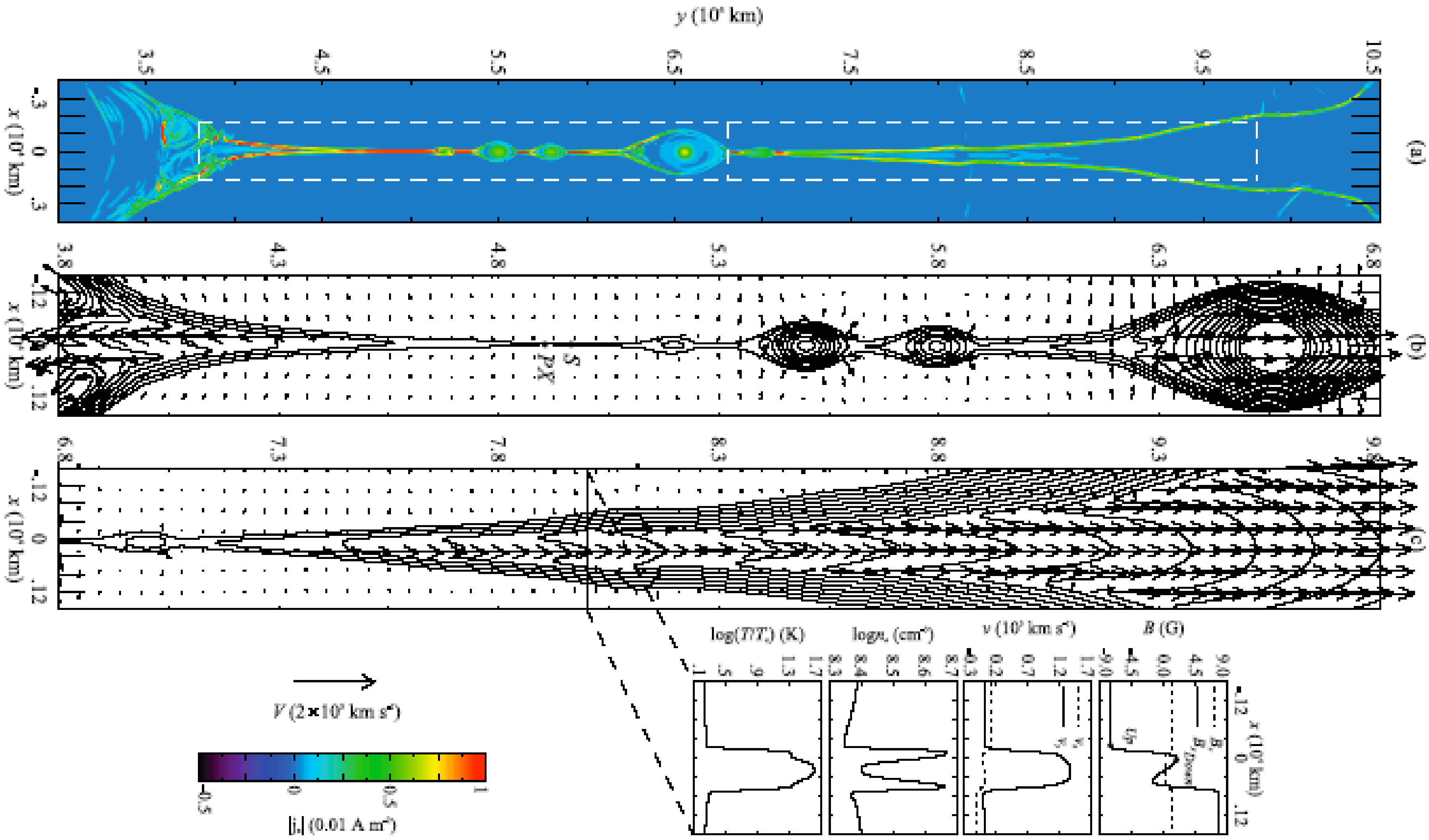


Predicted Flow in Current Layer



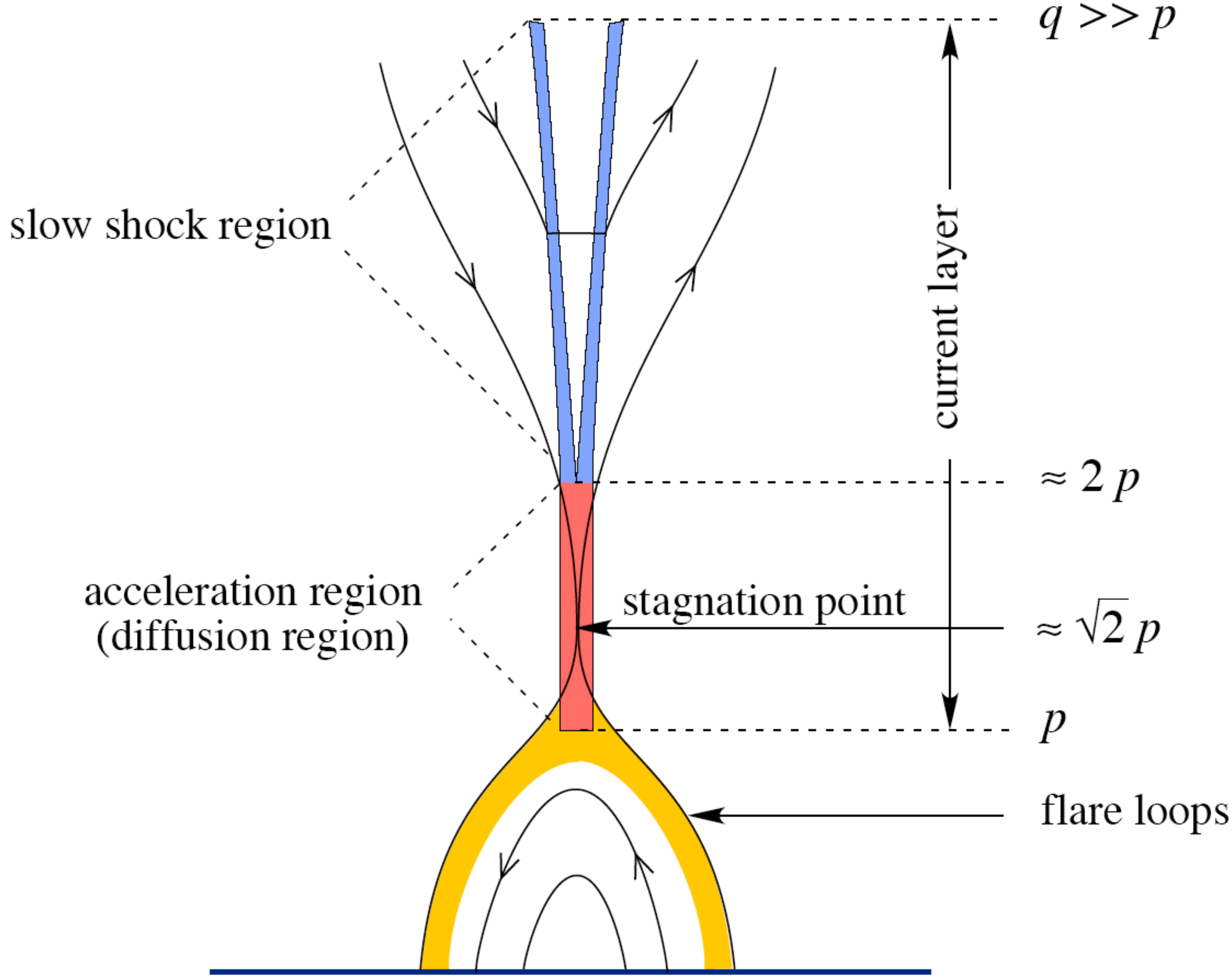
$\lambda \approx 20,000\text{km}$

2D MHD Simulation of Late Phase Reconnection



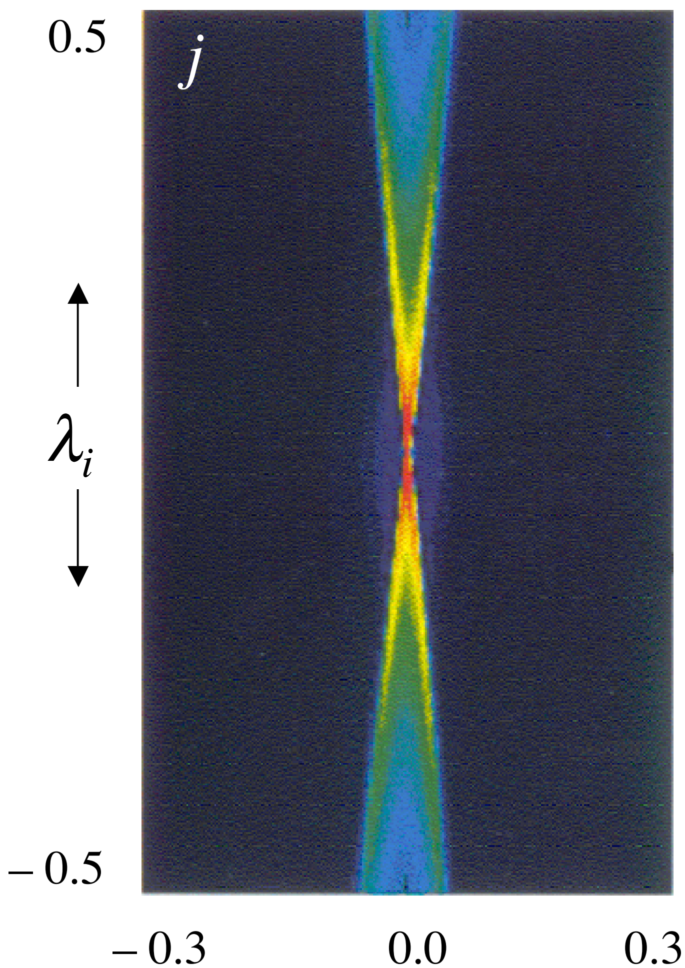
Mei et al. 2012

Predicted Reconnection Geometry During Late Phase for Uniform Resistivity



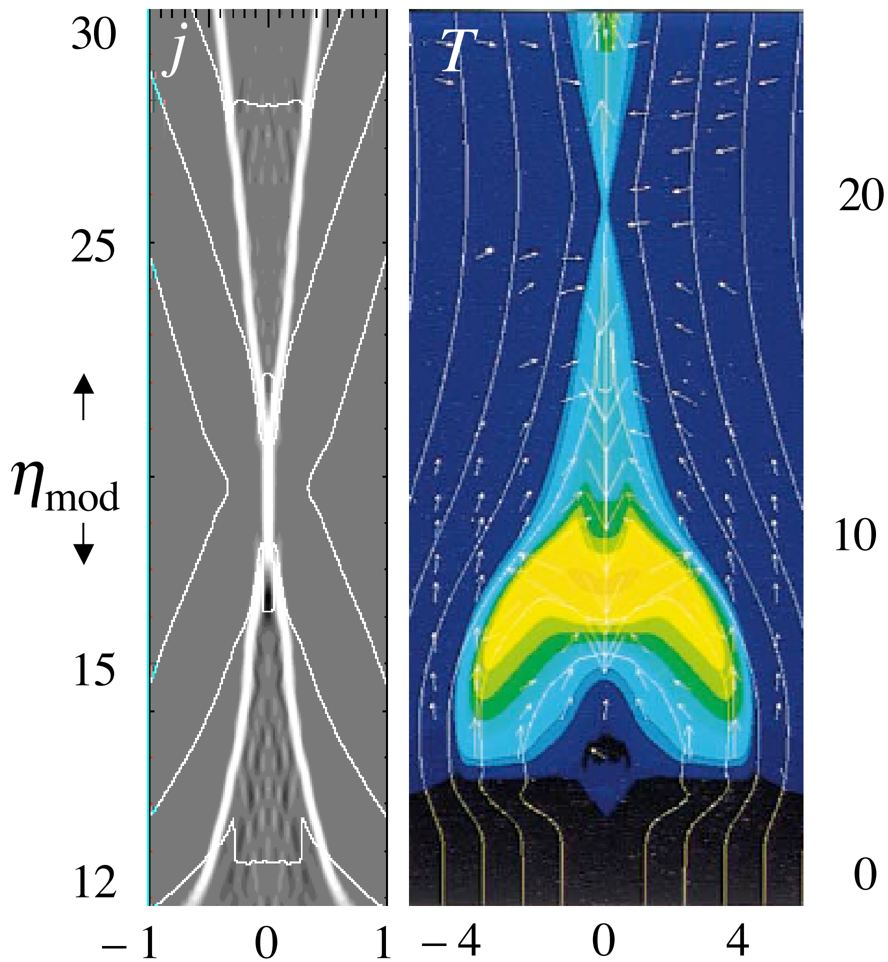
But What if Resistivity is Nonuniform?

Hall MHD simulation
(Ma & Bhattacharjee 1996)



λ_i : ion-inertial length $\approx$ 10 m

Current density
dependent resistivity:



(Yokoyama & Shibata 2001)

Unanswered Questions

1. What is the length of the region where reconnection outflows are accelerated?

   current observations ⇨ $< 10^4$ km

   scale of resistivity variation

2. Do slow shocks exist? If not, what replaces them?

   late phase of flare requires
   more than Sweet-Parker

3. How do 3D aspects change the 2D picture?